Low-Metallicity Star Formation: From the First Stars to Dwarf Galaxies
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The Luminosity Function of Long Gamma-Ray Burst and their rate at $z \geqslant 6$

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Abstract. We compute the luminosity function (LF) and the formation rate of long gamma ray bursts (GRBs) in three different scenarios: i) GRBs follow the cosmic star formation and their LF is constant in time; ii) GRBs follow the cosmic star formation but the LF varies with redshift; iii) GRBs form preferentially in low–metallicity environments. We then test model predictions against the *Swift* 3-year data, showing that scenario i) is robustly ruled out. Moreover, we show that the number of bright GRBs detected by *Swift* suggests that GRBs should have experienced some sort of luminosity evolution with redshift, being more luminous in the past. Finally we propose to use the observations of the afterglow spectrum of GRBs at $z \geqslant 5.5$ to constrain the reionization history and we applied our method to the case of GRB 050904.

Keywords. gamma rays: bursts, stars: formation, cosmology: observations, intergalactic medium

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1. Introduction

Long Gamma Ray Bursts (GRBs) are powerful flashes of high–energy photons occurring at an average rate of a few per day throughout the Universe up to very high redshift (the current record is $z = 6.29$). The energy source of a long GRB is believed to be associated to the collapse of the core of a massive star (see Mészáros 2006 for a review). One of the main goals of the *Swift* satellite (Gehrels et al. 2004) is to tackle the key issue of the GRB luminosity function (LF). Unfortunately, although the number of GRBs with good redshift determination has been largely increased by *Swift*, the sample is still too poor (and bias dominated) to allow a direct measurement of the LF. We use here the *Swift* 3-year data to constrain the GRB LF and its evolution (Salvaterra & Chincarini 2007, Salvaterra et al. 2008b). Moreover, we show a possible use of GRBs detected at $z \geqslant 5.5$ to study the history of reionization (Gallerani et al. 2008).

2. Model description

The observed photon flux, P, in the energy band $E_{\rm min} < E < E_{\rm max}$, emitted by an isotropically radiating source at redshift z is

$$P = \frac{(1+z)\int_{(1+z)E_{\rm min}}^{(1+z)E_{\rm max}} S(E)dE}{4\pi d_L^2(z)}, \quad (2.1)$$

where $S(E)$ is the differential rest–frame photon luminosity of the source, and $d_L(z)$ is the

luminosity distance. To describe the typical burst spectrum we adopt the functional form proposed by Band et al. (1993), i.e. a broken power–law with a low–energy spectral index α, a high–energy spectral index β, and a break energy $E_b = (\alpha - \beta)E_p/(2+\alpha)$, with $\alpha = -1$ and $\beta = -2.25$ (Preece et al. 2000). In order to broadly estimate the peak energy of the spectrum, E_p, for a given isotropic–equivalent peak luminosity, $L = \int_{1\,\mathrm{keV}}^{10000\,\mathrm{keV}} ES(E)dE$, we assumed the validity of the correlation between E_p and L (Yonetoku et al. 2004).

Given a normalized GRB LF, $\phi(L)$, the observed rate of bursts with $P_1 < P < P_2$ is

$$\frac{dN}{dt}(P_1 < P < P_2) = \int_0^\infty dz \frac{dV(z)}{dz}\frac{\Delta\Omega_s}{4\pi}\frac{\Psi_{\rm GRB}(z)}{1+z}\int_{L(P_1,z)}^{L(P_2,z)} dL'\phi(L'), \tag{2.2}$$

where $dV(z)/dz$ is the comoving volume element†, $\Delta\Omega_s$ is the solid angle covered on the sky by the survey, and the factor $(1+z)^{-1}$ accounts for cosmological time dilation. Finally, $\Psi_{\rm GRB}(z)$ is the comoving burst formation rate. In this work, we assume that the GRB LF is described by a power law with an exponential cut–off at low luminosities, i.e. $\phi(L) \propto (L/L_{\rm cut})^{-\xi}\exp(-L_{\rm cut}/L)$.

We consider three different scenarios: **i) no evolution model**, where GRBs follow the cosmic star formation and their LF is constant in time; **ii) luminosity evolution model**, where GRBs follow the cosmic star formation but the LF varies with redshift; **iii) density evolution model**, where GRBs form preferentially in low–metallicity environments. In the first two cases, the GRB formation rate is simply proportional to the global SFR, i.e. $\Psi_{\rm GRB}(z) = k_{\rm GRB}\Psi_\star(z)$. We use here the recent determination of the SFR obtained by Hopkins & Beacom (2006), slightly modified to match the observed decline of the SFR with $(1+z)^{-3.3}$ at $z \gtrsim 5$ suggested by recent deep–field data (Stark et al. 2006). For the luminosity evolution model, we also assume that the cut–off luminosity in the GRB LF varies as $L_{cut} = L_0(1+z)^\delta$. Finally, for density evolution case, the GRB formation rate is obtained by convolving the observed SFR with the fraction of galaxies at redshift z with metallicity below Z_{th} using the expression computed by Langer & Norman (2006). In this scenario, $L_{cut} = \mathrm{const} = L_0$.

3. Results

The free parameters in our model are the GRB formation efficiency $k_{\rm GRB}$, the cut–off luminosity at $z = 0$, L_0, and the LF power index ξ. We optimized the value of these parameters by χ^2 minimization over the observed differential number counts in the 50–300 keV band of BATSE (Stern et al. 2000). We find that it is always possible to find a good agreement between models and data. Moreover, we can reproduce also the 3–year differential peak flux count distribution in the 15-150 keV *Swift* band without changing the best fit parameters (Salvaterra & Chincarini 2007). We then check the resulting redshift distributions in the light of the *Swift* 3–year data, focusing on the large sample of GRBs detected at $z > 2.5$ and $z > 3.5$ (Fig. 1 panels a & b). The no evolution model is ruled out by the number of sure high-z GRBs. This result is robust since does not depend on the assumed SFR at high-z nor on the faint–end of the GRB LF. In conclusion, the existence of a large sample of bursts at $z > 2.5$ in the *Swift* 3-year data imply that GRBs have experienced some kind of evolution, being more luminous or more common in the past (Salvaterra & Chincarini 2007).

In order to discriminate between luminosity and density evolution models, we compute the number of luminous GRBs, i.e. bursts with isotropic peak luminosity $L \geqslant 10^{53}$ erg

† We adopted the 'concordance' model values for the cosmological parameters: $h = 0.7$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

s^{-1} in the 1-10000 keV band (Salvaterra et al. 2008b). We compare model predictions with the number of bright bursts detected by *Swift*. Conservatively, our data sample contains only bursts with a good redshift measurement and whose peak energy was well constrained by *Swift* itself or other satellites (such as HETE-2 or Konus-Wind). We stress here that this number represents a lower limit on the real number of bright GRBs detected, since some luminous bursts without z and/or E_p can be present in the *Swift* catalog. Results for the pure luminosity (density) evolution models are plotted in the panel c (d) of Fig. 1. Data are shown with the histogram where the shaded area takes into account errors on the determination of L. We find that models involving pure luminosity evolution requires $\delta \gtrsim 1.5$ to reproduce the number of known bright GRBs. On the other hand, models in which GRB formation is confined in low–metallicity environments fall short to account for the observed bright GRBs for $Z_{th} > 0.1$. Assuming $Z_{th} = 0.1\ Z_{\odot}$, the model reproduces the observed number of bright GRBs, taking also into account the errors in the determination of L. This means that essentially all bright bursts present in the 3-year *Swift* catalog have a measured redshift and well constrained peak energy. So, although this model can not be discarded with high confidence, the available data indicate the need of some evolution in the GRB LF even for such a low value of Z_{th}. For $Z_{th} = 0.3\ Z_{\odot}$, as required by collapsar models (MacFadyen & Woosley 1999), only ~ 6 bursts with $L \geqslant 10^{53}$ erg s^{-1} should have been detected in three year, largely underpredicting the number of *Swift* sure identifications. Thus, pure density evolution models, where the GRB LF is constant with redshift, are ruled out by the number of

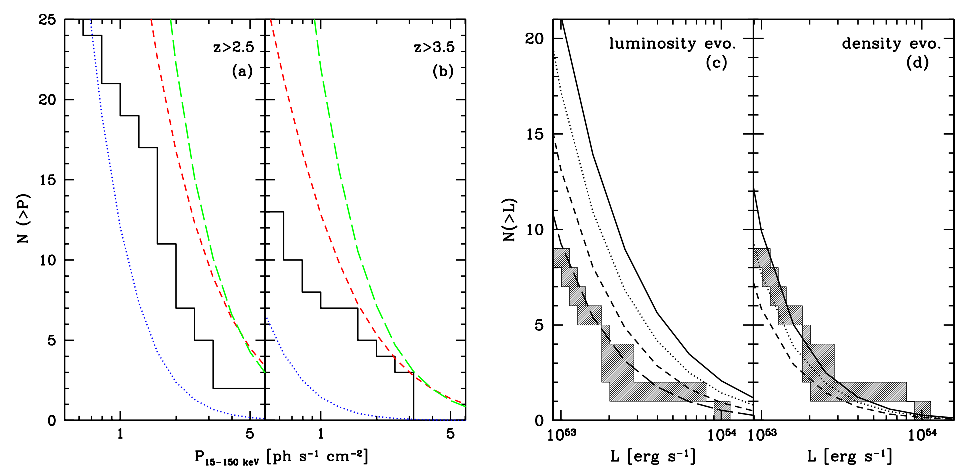

Figure 1. Panels a & b: cumulative number of GRBs at $z > 2.5$ (a) and at $z > 3.5$ (b) as a function of the photon flux P. Dotted line refers to the no evolution model, short dashed to the luminosity evolution model ($\delta = 1.5$) and long-dashed to the density evolution model ($Z_{th} = 0.1\ Z_{\odot}$). The number of sources detected by *Swift* in three years is shown as solid histogram. Note that the observed detections are lower limits, since many high–z GRBs can be missed by optical follow–up searches. A field of view of 1.4 sr for *Swift* is adopted. **Panels c & d:** cumulative number of luminous GRBs detected by *Swift* in three years, shown with the histogram, as function of the isotropic equivalent peak luminosity, L. Shaded area takes into account the errors on the determination of L. Note that the data are to be considered as lower limits of the real number of *Swift* detections. For pure luminosity evolution models (panel c): solid line is for $\delta = 3$, dotted line for $\delta = 2.5$, short–dashed line for $\delta = 2$, and long–dashed for $\delta = 1.5$. For pure density evolution models (panel d): Solid line is for $Z_{th} = 0.1\ Z_{\odot}$, dotted line is for $Z_{th} = 0.2\ Z_{\odot}$, and short–dashed line is for $Z_{th} = 0.3\ Z_{\odot}$.

bright GRBs. In conclusion, available data suggest that GRBs have experienced some luminosity evolution with cosmic time.

4. GRBs from the reionization epoch

We can now compute a robust lower limit on the number of bursts detectable by *Swift* at very high-z. Assuming a trigger threshold $P \geqslant 0.4$ ph s^{-1} cm^{-2}, at least $\sim 5-10\%$ of detected GRBs should lie at $z \geqslant 5$, with $> 1-3$ GRB yr^{-1} at $z \geqslant 6$. These numbers double by lowering the *Swift* trigger threshold by a factor of two (Salvaterra et al. 2008a).

High-z GRBs are a useful and unique tool to study the Universe near and beyond the reionization epoch. Gallerani et al. (2008) have studied the possibility to constrain the reionization history using the statistics of the dark portions (gaps) produced by intervening neutral hydrogen along the line of sight (LOS) in the afterglow spectra of GRB at $z \geqslant 5.5$. Two reionization models, both consistent with available observations of the high-z Universe, are considered: *(i) early reionization model* (ERM) where $z_{reion} \sim 7$ and *(ii) late reionization model* (LRM) where $z_{reion} \sim 6$. Suppose now that a GRB at redshift $z_{\rm GRB}$ is observed at a given flux level in the J band, $F_{\rm J}$. We can then ask what is the probability that the largest of the dark gaps in its afterglow spectrum is found within a given width range. The results are shown in Fig. 2 for two different width ranges; the left (right) panels refer to the ERM (LRM) case. The isocontours correspond to a probability of 15%, 30%, 45%, and 60%. We find that the two models populate the $(z_{\rm GRB}, F_{\rm J})$ plane in a very different way. In particular, for largest gaps in the 40–80 Å range, the highest probability is obtained for fainter afterglows in the ERM than for the LRM. For largest gaps in the range 80–120 Å, the probability is in general higher in the LRM with respect to the ERM. Note that, in the ERM, only a few spectra should contain the largest gap in

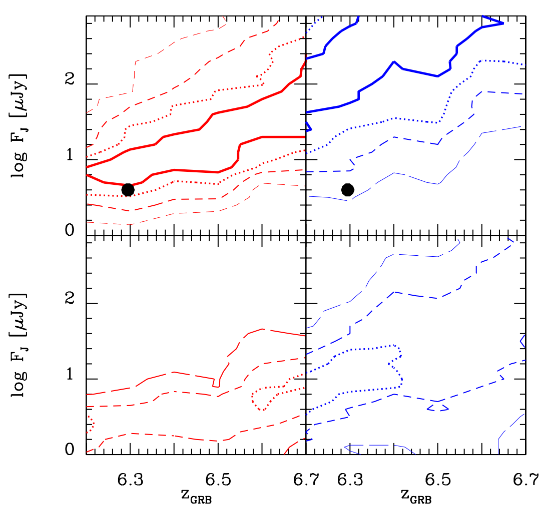

Figure 2. Isocontours of the probability that the afterglow spectrum of J-band flux $F_{\rm J}$ associated with a GRB at redshift $z_{\rm GRB}$, contains the largest gap in the range 40–80 Å (top panels) and in the range 80–120 Å (bottom panel). The left (right) panel shows the results for the ERM (LRM). The isocontours correspond to probability of 15% (long dashed line), 30% (short dashed line), 45% (dotted line), and 60% (solid line). The black point indicates the position in the $(z_{\rm GRB}, F_{\rm J})$ plane of GRB 050904.

this range for $F_{\rm J} \gtrsim 10-40$ μJy. Fig. 2 allows a straightforward comparison between data and model results. It is then natural to apply this procedure to GRB 050904 (black filled circle in Fig. 2). The probability to find the largest gap of 65 Å is $> 45\%$ in the ERM, i.e. almost half of the LOS contains the largest gap in the range 40–80 Å for a burst with the redshift and flux of GRB 050904. Such probability drops for the LRM to $\sim 15\%$ clearly indicating that in this case the GRB 050904 observation represents a much rarer event. Although a large sample of high-z GRBs is required before we conclude that a model in which reionization was complete at $z \sim 7$ is favored by the data, the discriminating power of the proposed method is already apparent.

This kind of analysis requires high signal-to-noise, high resolution spectra of GRB afterglow spectra at $z \geqslant 5.5$ obtained with the largest ground telescopes soon after the burst detection. To avoid wasting observing time, we developed a very effective strategy to spot reliable $z \geqslant 5$ candidates on the basis of promptly available information provided by *Swift* (Campana et al. 2007, Salvaterra et al. 2007). The selection criteria adopted are: long burst observed durations ($T_{90} \gtrsim 60$ s), faint γ-ray photon fluxes ($P \lesssim 1$ ph s^{-1} cm^{-2}), and no optical counterpart in the V and bluer filters of UVOT ($V \gtrsim 20$). We tested our selection procedure against the last ~ 2 years of *Swift* data showing that our method is very efficient and clean (i.e. no low-z interloper is present in the sample).

5. Conclusions

We have tested different formation and evolution scenarios for long GRB against the 3-year *Swift* dataset. We found that *Swift* data strongly rule out models in which GRBs follow the cosmic star formation and their LF is constant in time. In particular, the number of bright GRBs suggests that GRBs should have experienced some sort of luminosity evolution with cosmic time, being more luminous in the past. Finally we have shown that GRBs at $z \geqslant 5.5$ can be use to constrain the reionization history and we applied our method to the case of GRB 050904 at $z = 6.29$.

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